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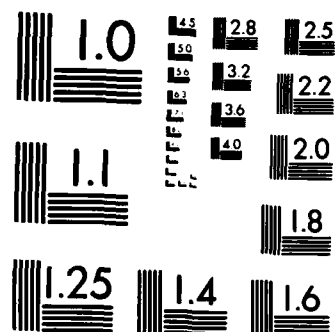
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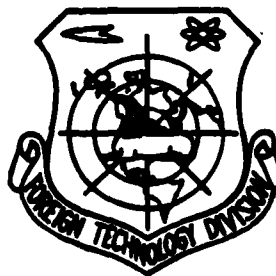
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THEORY OF THE REACTION SURFACE WITH $Le_f \approx 1$ AND ITS APPLICATION IN
THE OXIDATION-SUBLIMATION COUPLING PROCESS

by

Zhong Jiakang



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THEORY OF THE REACTION SURFACE WITH $Le_f \neq 1$ AND ITS APPLICATION IN THE OXIDATION-SUBLIMATION COUPLING PROCESS

Zhong Jiakang
(Zhejiang University)

ABSTRACT

This paper presents a theoretical analysis on the reaction surface of a locally similar laminar boundary layer with addition of mass and chemical reaction. Heat transfer and mass transfer correlations under the condition $(Le_f \neq 1)$ are derived. As an application of the theory of the reaction surface, the oxidation sublimation coupling process on the surface material is investigated. The transition mechanism and transformation condition of the oxidation and sublimation processes from rate-controlled to diffusion-controlled regimes are described. The phenomenon that the rate-sublimation is involved in diffusion-controlled oxidation regime is shown. Comparisons with the experimental data are made for the case of graphite stagnation ablation, and quantitative agreement is found. (Translations: Chinese Abstracts, Reprints)

/27

SYMBOLS

a_E	condensation coefficient
C_i	fractional mass of a unit element
C_{pi}	isobaric specific heat of a unit element
C_{pf}	$\sum C_i C_{pi}$ freezing specific heat
D_i	equivalent or effective two-dimensional diffusion coefficient
E	activation energy
$f(\eta)$	simplified flow function
h_i	$\int_0^T c_p dT + h_i^0$, enthalpy of a unit element
h_i^0	formation enthalpy of a unit element
h_s	$h + \frac{1}{2}u^2$ total enthalpy

h_{Ts}	$h_i - \sum_i c_i h_i^0$, freezing total enthalpy
k_o	surface oxidation rate constant
S_c	$\mu/\rho D_i$ Schmidt number
\bar{S}_c	$(S_c)/(1 + \alpha\beta)$
T	temperature
u, v, x, y	velocity components in the x, y directions
\dot{w}_i	formation rate of chemical substance
α_{ki}	$\nu_{ki} M_k / \nu_i M_i$, quantitative relationship
β	$2d \ln u_i / d \ln g$
ΔQ_{J_2}	$h_j^0 - h_{j_2}^0$, dissociation heat
ΔQ_{CJ}	$h_j^0 - \frac{M_{Cj}}{M_j} h_{Cj}^0 + \frac{M_c}{M_j} h_c^0$, reaction heat
ΔQ_E	$h_C^0 - h_E^0$ dissolution heat
λ_E	sublimational fraction of a unit element E
μ	viscous coefficient
ν	quantitative coefficient
ρ	mass density
K_f	conduction coefficient of freezing heat
L	$\rho\mu/\rho_e\mu_e$
\bar{L}	$L/(1 + \alpha\beta)$
Le_f	$\rho D_i C_H / K_f$, freezing Lewis number
L_E	$h_E - h_E^0$ (solid), sublimation heat
M_i	molecular weight of a unit element
\bar{M}	$[\sum_i (c_i / M_i)]^{-1}$, average molecular weight
p	pressure
Pr_f	$C_H \mu / K_f$, freezing Prandtl number
\bar{Pr}_f	$Pr_f / (1 + \alpha\beta)$
r	radius of revolution
R	universal gas constant
R_b	radius of the head of the stagnation point
E	chemical element of the sublimational element or surface material
e	condition outside the fringe of the boundary layer
eq	equilibrium condition
i	unit element
K	chemical substance
s	stagnation point

w wall

Superscript

* condition on the reaction surface
' derivative against η

Superscript

This paper received on March 17, 1982

Many references (such as [1] and [2]) concerning the theory of the reaction surface in the chemical boundary layer have been published. In prior studies, their effort mostly considered the characteristics of steady flow or assumed that the Lewis number was 1. This paper uses the Blasius function to solve for the characteristic reaction surface, and conducts a theoretical analysis on the reaction surface of a locally similar laminar boundary layer with addition of mass and chemical reaction. We derive some mass transfer and heat transfer correlations when $Le_f \approx 1$, and these correlations are very convenient for engineering applications. As an application of the theory of reaction surface, we conduct a study into the coupled oxidation-sublimation process on the surface material and describe the transition mechanism and transformation condition of the oxidation and sublimation processes from rate controlled to diffusion controlled regimes. The phenomenon that the rate sublimation is included in diffusion controlled oxidation regime is shown. Comparisons with the experimental data are made for the case of graphite stagnation ablation, and quantitative agreement is found.

I. Theory of the reaction surface

We introduce the Blasius function G into the boundary layer equation and use G as the new independent variable; G is defined as

$$G(\eta; f_w, Z) = G'(0; f_w, Z) \int_0^\eta e^{-\int_0^\eta f_w' d\eta} d\eta \quad (1.1)$$

Here

$$G'(0; f_w, Z) = 1 / \int_0^\infty e^{-\int_0^\eta f_w' d\eta} d\eta \quad (1.2)$$

assuming that the gaseous reaction in the boundary layer is confined on an infinitely thin cross-section (the reaction surface), and the flows on two sides of the reaction surface are chemically frozen. Based on this, we can derive the following reaction surface equations from the boundary layer equations of multi-component reaction gases [3] ($j = 0$ is the horizontal flow, $j = 1$ is the axi-symmetrical flow):

$$\text{momentum equation} \quad f' = G_1 \quad (1.3)$$

diffusion equation

$$\frac{c_{i0} - c_i^*}{1 - G_1^*} - \frac{c_i^* - c_{iw}}{G_1^*} = - \frac{\bar{S}_i}{G_1^*} \bar{w}^* \quad (1.4)$$

energy equation

$$\frac{(h_{T_0})_0 - h_{T_1}^*}{1 - G_1^*} - \frac{h_{T_1}^* - h_{T_w}}{G_1^*} = \frac{\bar{P}_{r_1}}{G_1^*} \sum_i \bar{w}_i^* h_i^* \quad (1.5)$$

Here

$$\xi = \int_0^x \rho_0 \mu_0 u_0 r^2 dx, \quad \eta = \frac{u_0 r^2}{\sqrt{2\xi l}} \int_0^y \rho dy \quad (1.6)$$

$$\bar{w}^* = \frac{2\xi}{\rho_0 \mu_0 u_0^2 r^2} \frac{\dot{w}_w^*}{\rho^*} \quad (1.7)$$

and $G_1 = G(\eta; f_w, 1)$, $G_2 = G(\eta; f_w, \bar{S}_i)$ and $G_3 = G(\eta; f_w, \bar{P}_{r_1})$.

There are existing accurate numerical values of the function

$G(\eta; f_w, Z)$ that we can readily use [4]. We have already made the following assumptions: (1) the flow is locally similar; (2) neglect the small differences of the specific heat between the components; (3) l , Pr_f and S_c are all constants; (4) neglect the dissipation term in the energy equation (the dissipation effect can be incorporated in the computation of the recovered enthalpy); (5) the pressure gradient term in the momentum equation will be considered, but that term will be approximated as $\beta[(\rho_0/\rho) - 1] \approx a\beta f''$; here a is a selective constant, we can set $a = 1 + 2.6 (T_w/T_c)$ [5].

By using the exchanged parameters B and θ_i of the introduced mass defined as

$$(\rho v)_w = \alpha_i(0; f_w) B, \quad (\rho_i v_i)_w = \theta_i (\rho v)_w \quad (1.8)$$

with

$$\alpha_i(0; f_w) = \frac{\sqrt{1}}{\bar{S}_i} \frac{\rho_i \mu_i \gamma_i}{\sqrt{2\xi}} G'(0; f_w, \bar{S}_i) \quad (1.9)$$

We can write the mass fraction of a compound on the surface as

$$c_{iw} = \frac{c_i^* + G_i^* \theta_i B}{1 + G_i^* B} \quad (1.10)$$

Combining (1.4) and (1.8), the concentration relation on the reaction surface is

$$c_i = \frac{(1 + G_i^* B) c_{ie} + (1 - G_i^*) \theta_i B}{1 + B} + \frac{(1 - G_i^*)(1 + G_i^* B)}{1 + B} \frac{\bar{S}_i}{G_i^*} w_i^* \quad (1.11a)$$

Or the mass fraction of the chemical element is

$$\bar{c}_K = \frac{(1 + G_i^* B)(\bar{c}_K)_e + (1 - G_i^*) \bar{\theta}_K B}{1 + B} \quad (1.11b)$$

with

$$\bar{c}_K = \sum_i \alpha_{Ki} c_i \quad \text{和} \quad \bar{\theta}_K = \sum_i \alpha_{Ki} \theta_i$$

The expression of the enthalpy on the reaction surface can be obtained from (1.4), (1.5) and (1.10) as

$$h_{T_s} = G_i^* (h_{T_s})_e + (1 - G_i^*) h_{T_w} + I^* G_i^* \Delta h_{ch} \quad (1.12)$$

Here we have

$$\Delta h_{ch} = \sum_i h_i^* [c_{ie} - (1 + B) c_{iw} + \theta_i B] \quad (1.13)$$

$$I^* = L e_i G_i^* (1 - G_i^*) / G_i^* (1 - G_i^*) \quad (1.14)$$

The temperature on the reaction surface can be computed based on $h_{T_s}^*$. This is to say that

$$C_H^* T^* = h_{T_s}^* - \frac{1}{2} u_\infty^2 G_i^{*2} \quad (1.15)$$

By using (1.12), the heat flux from the boundary layer to the surface can be expressed as

$$-q_w = \alpha_i(0; f_w) \left[(h_{T_s})_e - h_{T_w} + I^* \Delta h_{ch} + I(0) B \sum_i h_i^* (c_{iw} - \theta_i) \right] \quad (1.16)$$

Here we have

$$\alpha_i(0; f_w) = \frac{\sqrt{1}}{Pr_i} \frac{\rho_i \mu_i \gamma_i}{\sqrt{2\xi}} G'(0; f_w, Pr_i) \quad (1.17)$$

$$I(0) = L e_i G'(0; f_w, \bar{S}_i) / G'(0; f_w, Pr_i) \quad (1.18)$$

Based on the definition of B and the $-f_w$ boundary condition correlation, we can find the relationship between the two as

$$-f_w = G'(0; f_w, \bar{S}_e) B / \bar{S}_e \quad (1.19)$$

During the computation of mass transfer and heat transfer, we need to know the value of $G'(0; f_w, Z)$. For engineering applications, we will use the following approximation equation to compute the injection rate ($-f_w$) and its influence on $G'(0; f_w, Z)$

$$G'(0; f_w, Z) = G'(0; 0, Z) - \zeta_1(-f_w Z) + \zeta_2(-f_w Z)^2 \quad (1.20)$$

Here

$$G'(0; 0, Z) = 0.47Z^{1/2} \quad (1.21)$$

The values of the constants ζ_1 and ζ_2 are listed on Table 1. They are related to Z. After detailed numerical comparisons [4], this equation gives very high accuracy. So the substitution of (1.19) into (1.20) can give a second order equation describing the relationship between $G'(0; f_w, Z)$ and B as

$$a[G'(0; f_w, \bar{S}_e)]^2 + bG'(0; f_w, \bar{S}_e) + G'(0; 0, \bar{S}_e) = 0 \quad (1.22)$$

Here $a = \zeta_2 B$ and $b = -(1 + \zeta_1 B)$.

TABLE 1. The values of ζ_1 and ζ_2

Z	0.6	0.7	0.8	0.9	1.0	2.0
ζ_1	0.770	0.757	0.753	0.745	0.732	0.702
ζ_2	0.0971	0.163	0.172	0.193	0.192	0.203

$G'(0; f_w, \bar{S}_e)$ and

There is an approximated relationship between $G'(0; f_w, \bar{P}_{r1})$

$$\frac{G'(0; f_w, \bar{S}_e)}{G'(0; f_w, \bar{P}_{r1})} = Le^n \quad (1.23)$$

Here the exponent n is related to the injection amount, and their relationship is given by the table below.

$-\sqrt{2}f_w$	0	0.5	0.75	1.0
n	-1/3	0	1/2	1

Beside this, the effect of density-viscosity on the mass transfer and heat transfer is expressed by $\sqrt{l} = \sqrt{\rho\mu/(\rho_s\mu_s)}$. We can estimate the value of l by using the reference temperature method, or to simply take $l = (\rho_s\mu_s/\rho\mu)^{0.26}$.

II. Study into the coupled oxidation-sublimation process

By using results from the above study, we will now examine the coupled oxidation-sublimation (or evaporation) process of the surface material. For convenience, we will specify that the oxygen in the boundary layer will only form EO with the surface material (expressed as chemical element E) and the sublimated element of E (may be vapor of a single molecule, two molecules or multi-molecules) will only form two-molecule EO and EN with the molecules of oxygen and nitrogen. We also assume that the reaction between the sublimated element and air is a fast reaction (such as the reaction between the carbon vapor and the air); then there exists a complete reaction surface. On this surface $(c_o + c_{o_2})^* = 0$ and $\sum_i c_i^* = 0$. The position of the complete reaction surface is

$$G_1^* = (B - B_0)/B(1 + B_0) \quad (2.1) \quad /31$$

Here

$$B_0 = (M_E/M_O)(c_o + c_{o_2})_s + (e/(1 + e))(M_E/M_N)(c_N + c_{N_2})_s$$

and $(M_{EN}/M_N)e = c_{EN}^*/(c_N + c_{N_2})^*$. , e is the carbon consumption of the nitrogen-carbon reaction.

We will now treat the oxidation process and the sublimation process separately, and use the sublimation ratio λ (mass loss due to sublimation/total mass loss) to establish the linkage between the two. Both the oxidation and the sublimation processes are formed by two basic processes: one is a surface chemical dynamical process, the other is a convection-diffusion process in which either the reaction material (oxygen) flows toward the surface or the sublimated material flows out of the surface.

Between these two processes, the slower one of the two will be dominating. Especially when the rate of one of the basic processes is far less than that of the other, the slower one of the two controls the entire process (oxidation or sublimation). At this time, the rate of mass loss from the surface actually equals the value of the slower basic process.

During the oxidation process, $B \ll B_0$ at the complete reaction plane on the surface. The rate of mass loss on the surface can be determined by a combination of the wall dynamics factor and the convection-diffusion factor within the boundary layer. It can be expressed as

$$(1 - \lambda)(\rho v)_w = \frac{[(c_o + c_{o_s})_e + (e/1 + e)(M_o/M_N)(c_N + c_{N_s})_e]/(1 + B)}{(1/\alpha_{sh}) + (1/\alpha_{d_s})} \quad (2.2)$$

Here we have

$$\alpha_{sh} = (M_E/M_o)(1 + B)^{1-n}(B_0 - B)^{n-1}k_{oc}e^{-E/RT_w}(\bar{M}_w/M_o)^n p^n,$$

$$\alpha_{d_s} = (M_E/M_o)(1 - \lambda)(1 + B)\alpha_s(0; f_w)$$

They are the coefficient of the oxidation rate and the equivalent convection-diffusion coefficient, respectively. The former characterize the speed of the oxidation reaction of the surface material under a certain concentration of oxygen, and the latter characterize the speed of transport of oxygen to the surface which is a complicated function related to the boundary layer factor.

At low surface temperatures of ($\alpha_{sh} \ll \alpha_{d_s}$), expression (2.2) can lead to the limiting case of oxidation rate control:

$$B \rightarrow 0, (c_o + c_{o_s})_w \rightarrow (c_o + c_{o_s})_e, (\rho v)_w \rightarrow k_{oc}e^{-E/RT_w} \left(\frac{\bar{M}_w}{M_o} p \right)^n (c_o + c_{o_s})_e^2 \quad (2.3)$$

For low surface temperature ($\alpha_s \ll \alpha_d$), we can derive the limiting condition for the diffusion-controlled oxidation as:

$$B \rightarrow B_s, (c_0 + c_{O_2})_w \rightarrow 0, (\rho v)_w \rightarrow \alpha_s(0; T_w) B_s. \quad (2.4)$$

During sublimation, the mass loss from the surface as determined by a combination of the surface sublimation dynamics factor and the convection-diffusion factor is

$$1(\rho v)_w = \sum_E \frac{c_{E,eq,w}}{1/(\alpha_s)_E + (1/\alpha_d)} \quad (2.5)$$

Here $(\alpha_s)_E = \alpha_E \bar{M}_w p / \sqrt{2\pi R M_E T_w}$ is called the coefficient of the rate of sublimation for the sublimated component E. It represents the speed of the sublimation process on the surface under a specific concentration of vapor;

$$\alpha_d = [(1 + G_s^*)B/G_s^*]\alpha_s(0; t_w) - [(1 + B)B/(B - B_0)]\alpha_s(0; t_w)$$

is an equivalent convection-diffusion rate coefficient; it represents the speed of disappearance of the sublimated material from the surface and it is also a complicated function of the boundary layer factor.

When the surface temperature is not too high, we have $((\alpha_s)_E \ll \alpha_d)$

$$B \rightarrow B_0, \quad c_{E,w} \rightarrow 0, \quad \lambda(\rho v)_w \rightarrow \sum_E (\alpha_s)_E c_{E,eq,w} \quad (2.6)$$

This is a limiting condition for the rate-controlled sublimation. In the region, the complete reaction plane is still maintained on the surface; the sublimated element is instantaneously burned completely on the surface. The oxygen that is transported to the surface is partially consumed by the sublimated element, and the remaining part then forms the oxidation reaction with the solid wall. The mass loss on the surface equals the value of diffusion-controlled oxidation. This indicates that during the coupled oxidation-sublimation process, the rate controlled sublimation is contained in the region of diffusion controlled oxidation, and the rate controlled part of the sublimation increases with increasing temperature, until the surface mass loss is completely due to sublimation ($\lambda = 1$). The sublimation ratio can be determined by the equation below

$$\lambda = \sum_E (\alpha_s)_E c_{E,eq,w} / \alpha_s(0; t_w) B_0 \quad (2.7)$$

When the surface temperature is sufficiently high $((\alpha_s)_E \gg \alpha_d)$ we have

$$B \rightarrow \left(\sum_E c_{E,eq,w} + B_0 \right) / \left(1 - \sum_E c_{E,eq,w} \right), \quad c_{E,w} \rightarrow c_{E,eq,w}, \\ (\rho v)_w \rightarrow \alpha_s(0; t_w) B \quad (2.8)$$

This is the diffusion-controlled sublimation regime. This is equivalent to the condition that the wall surface maintains a limiting equilibrium sublimation condition when the transport in the boundary layer is very slow so that the sublimated gases cannot flow away from the surface fast enough. At this time,

the solid wall oxidation reaction no longer exists ($\lambda = 1$) since the complete reaction plane has gone away from the surface.

III. Results and conclusions

We will now discuss the oxidation and sublimation of carbon material as an example. Figure 1 shows the variation of the mass exchange parameter B with surface temperature T_w during a non-equilibrium oxidation process. The surface oxidation dynamics data are obtained for (1) "slow reaction": $n = \frac{1}{2}$, $E = 42.3$ Kcal/g molecule, $k_o = 2.18 \times 10^4$ g/cm²S (atmospheric pressure)^{1/2}; (2) "fast reaction": $n = \frac{1}{2}$, $E = 44.0$ Kcal/g molecule, $k_o = 3.28 \times 10^8$ g/cm²S (atmospheric pressure)^{1/2}. The former corresponds to heat dissolution graphite, and the latter corresponds to common industrial graphite [7]. By defining a Damköhler number $D_m = \alpha d_1 / \alpha_{ch}$, the transformation condition of the controlled regime can be determined. For example, we can select $D_m = 100$ and 0.01 (corresponding to B values of 0.00173 and 0.171 , respectively) as the boundary values for the non-equilibrium transition regime. For the flow around the stagnation point under the condition that $R_p = 10$ Cm, the corresponding temperature boundary values for the "fast reaction" are $770K$ and $1000K$, respectively. For "slow reaction" the corresponding values are $1100K$ and $1700K$ respectively (Figure 1). Under the special condition of flow around the stagnation point, the boundary value of temperature is determined by the radius of the head and the oxidation dynamics data. Since $n = 1/2$, pressure has nothing to do with it. We can select the air concentration outside the fringe of the boundary layer to be $(c_o + c_{O_2})_e = 0.23$ and $(c_N + c_{N_2})_e = 0.77$ in our computation. Figure 2 shows the B versus T_w curves for the equilibrium as well as the non-equilibrium sublimation process. The major compositions of the carbon vapor are assumed to be C , C_2 , C_3 , C_4 and C_5 . The equilibrium concentration of the sublimated element can be compiled from the equilibrium vapor pressure $p_{E,eq}$ as $c_{E,eq} = M_E p_{E,eq} / \bar{M} p$. The equilibrium vapor pressure of each carbon element is also given

in the JANAF thermodynamics table [8], and can be computed by the following equation

$$\log_{10} p_{E,eq} = a + b/T(K) \quad (3.1)$$

The constants a and b are listed in Table 2. Table 2 also shows the condensation coefficients of the carbon vapor a_E . These coefficients are obtained from [9].

Figure 2 shows a curve with the assumption that $a_E = 1$. We can see that the $a_E = 1$ results is very similar to the equilibrium value, while the deviation is larger when a_E is obtained from the values in Table 2.

TABLE 2. The condensation coefficient of the carbon vapor a_E and the constants a and b in the equilibrium constant equation

E	C	C ₁	C ₂	C ₃	C ₄
a_E	0.24	0.50	0.023	0.25	0.0019
a	8.096	9.607	9.627	10.013	10.464
b	-3.709	-4.262	-3.960	-4.889	-4.927

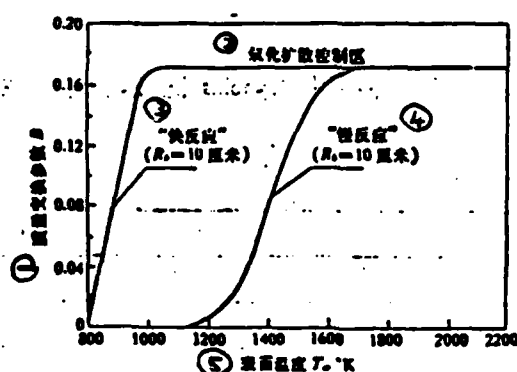


Figure 1. The variation of B with T_w in an oxidation process. 1--mass exchange parameter B; 2--diffusion-controlled oxidation regime; 3--"fast reaction" ($R_p=10\text{cm}$); 4--"slow reaction" ($R_p=10\text{cm}$); 5--surface temperature T_w °K

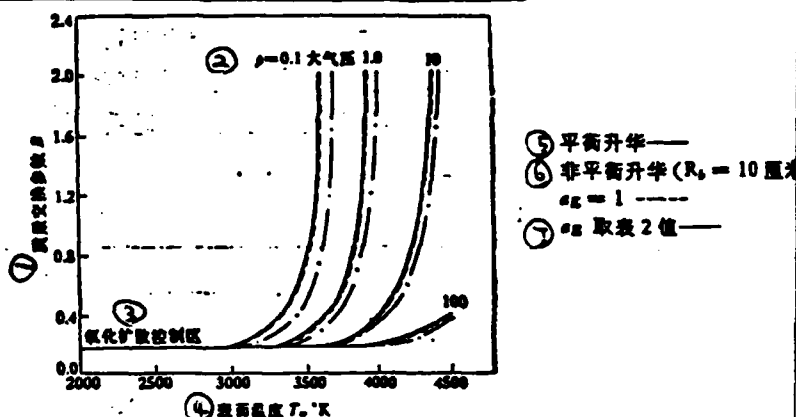


Figure 2. The variation of B with T_w in a sublimation process. 1--mass exchange parameter B; 2-- $p=0$, k atmospheric pressure; 3--diffusion-controlled oxidation regime; 4--surface temp.; 5--equilibrium sublimation; 6--non-equilibrium sublimation; 7-- a_E obtained from values in Table 2

Based on the energy equilibrium relation at the gas-solid interface and (1.16), the heat flux into the interior of the solid q_b can be expressed as

$$q_b = \alpha_h(0; f_w)[(h_{T_s})_s - h_{T_w} + I^* \Delta \bar{h}_{ch} - I(0)B\bar{L}_s] + \alpha q_{r,s} - \sigma T_w^4 \quad (3.2)$$

Here we have

$$\Delta \bar{h}_{ch} = - \sum_{j=0, N} [(c_{I_j})_s - (1+B)(c_{I_j})_w] \Delta Q_{I_j} + \sum_{j=0, N} [(c_j + c_{I_j})_s - (1+B)(c_j + c_{I_j})_w] \Delta Q_{C_j} + \sum_{k=C_1}^{C_2} [(1+B)c_{E,w} - \lambda_E B] \Delta Q_E \quad (3.3)$$

$$\bar{L}_s = (1-\lambda)L_s - \sum_{E=C}^{C_2} \lambda_E L_E \quad (3.4)$$

TABLE 3. Reaction heat (cal/g)

① 气相反应热		② 升华热	
$\Delta Q_{O_2} = 3700$	$\Delta Q_{C_2} = 6100$	$L_C = 14200$	$L_{C_2} = 4600$
$\Delta Q_{N_2} = 8000$	$\Delta Q_{C_2} = 9200$	$L_{C_1} = 8100$	$L_{C_2} = 3700$
$\Delta Q_{CO} = 1600$	$\Delta Q_{C_2} = 9600$		
$\Delta Q_{CN} = 12500$	$\Delta Q_{C_2} = 10500$	$L_{C_2} = 5000$	

1--gas phase reaction heat; 2--sublimation heat

The quantities $\alpha q_{r,s}$ and σT_w^4 represent the energy loss due to the energy transmitted to the wall by the heated gas radiation and the outward radiation from the surface of the wall, respectively. The various types of reaction heat are listed in Table 3. From (3.2) we can see that the reaction plane can directly influence the value of q_b through the factor $I^* \Delta h_{ch}$. When $I^* = I(0)$, or when the reaction plane is in the wall surface, (3.2) can be simplified into the result of Lees [6] for the frozen boundary layer.

Finally, in order to test the accuracy of our theory, we have conducted computation on the ablation of graphite at the axial-symmetric stagnation point in dissoluted air. The heat transfer coefficient of the dissoluted air $\alpha_h(0.0)$ for the flow around the stagnation point can be approximated as

$$\alpha_h(0; 0) = 0.113 \sqrt{p_\infty / R_s} \quad \text{g/cm}^2 \cdot \text{s} \quad (3.5)$$

Here p_s is in atmospheric pressure, R_b is in Cm. Due to the unstable nature of the transport coefficient, we select the following two values (a) $Pr_f = (Pr_f)_{N_s} = 0.7$ and $Sc = (Sc)_{N_s} = 0.965$; (b) $Sc = 0.965$ and $Le_f = 1$, and assume that the sublimation is in equilibrium. The comparison of the theoretical values and experimental values is shown in Table 4. Under a low pressure environment, the graphite is basically in thermal chemical ablation, and we can see that there is a quantitative agreement between the theoretical value and the experimental value.

By using the turbulent transport coefficient to replace the laminar transport coefficient in the boundary layer equation and use the Reynolds approximation, this method can be expanded to the turbulent boundary layer.

TABLE 4. Comparison between theoretical value and experimental value.

p_s atm.	T_s K	① $(\rho v)_{\infty} \sqrt{R_b/p_s}$ (克/厘米 ²)(厘米/大气压) ^{1/2}		
		② 理论值		③ 测量值
		(a)	(b)	
0.12	2500	0.0140	0.0174	0.017(2520—2620K)
	2600	0.0141	0.0175	
0.12	3600	0.0751	0.0931	0.069—0.077 (3650K) 0.122—0.135 (3700K)
	3700	0.0803	0.0995	
0.32	2500	0.0140	0.0173	0.018 (2520—2700K)
	2700	0.0141	0.0175	
0.30	3000	0.0150	0.0185	0.017 (3000—3200K)
	3200	0.0169	0.0209	
0.32	3600	0.0389	0.0482	0.037—0.052 (3600K) 0.062—0.066 (3710K)
	3700	0.0573	0.0709	

(a) $Pr_f = (Pr_f)_{N_s} = 0.7$ 和 $Sc = (Sc)_{N_s} = 0.965$
 (b) $Sc = 0.965, Le_f = 1$

1--(g/cm²) (Cm/atmospheric pressure)^{1/2}; 2--theoretical value;
 3--measured value

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THEORY OF THE REACTION SURFACE WITH $Le \neq 1$

AND ITS APPLICATION TO INVESTIGATION ~~IN THE~~ ^{in the} OXIDATION-SUBLIMATION COUPLING PROCESS

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Abstract

This paper presents a theoretical analysis of the reaction surface for the locally similar laminar boundary layer with addition of mass and chemical reactions, Heat-transfer and mass-transfer correlations for $Le \neq 1$ are obtained. As an application the oxidation-sublimation coupling process is investigated. The transition mechanism from rate-controlled to diffusion-controlled regimes is described. The Phenomenon that the rate-sublimation is involved in diffusion-controlled oxidation regime is displayed. Comparisons with the experimental data are made for the case of graphite stagnation ablation and quantitative agreement is found.

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